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A deglacial palaeomagnetic master curve for Fennoscandia — Providing a dating template and supporting millennial-scale geomagnetic field patterns for the past 14 ka

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ABSTRACT

Reconstructions of palaeomagnetic secular variation (PSV) in sediment cores can be compared to well-dated regional PSV master curves to infer deposition age. The existing PSV master curve for Fennoscandia, “Fennostack” (Snowball et al., 2007), is limited to the past 10 ka. In this study, we construct a deglacial (for the interval 14–11 ka) PSV master curve for Fennoscandia by including data from a number of existing studies in the region, updating geochronologies where necessary. We also produce new deglacial PSV data from Baltic Sea long-core sediments. By selecting three suitable sites, one in southern Sweden and two in northwest Russia, we produce, for the first time, a deglacial PSV master curve for Fennoscandia, which will provide a useful alternative dating tool for deglacial time intervals, especially considering that deglacial sediments are often unsuitable for ^{14}C dating. Additionally, we use the deglacial PSV master curve to assess current hypotheses regarding geomagnetic field changes. Time varying geomagnetic field models constrained by Holocene PSV data from around the globe have predicted the presence of latitudinal and longitudinal patterns in the position of the north geomagnetic pole (NGP). Specifically, a 1350 year cycle in NGP latitude has been noted, along with two preferred dominant mode longitudinal bands for NGP; in Europe and North America (Korte et al., 2011; Nilsson et al., 2011). Most PSV studies of sediment are, however, limited to the Holocene epoch. By combining our deglacial PSV master curve with ‘Fennostack’, we are able to assess general patterns in inclination for the past 14 ka, and compare these to a general prediction of regional inclination for the last 14 ka, based on an extrapolation of the latitudinal and longitudinal NGP periodicity noted by Nilsson et al. (2011). The model prediction suggests that the Fennoscandian PSV for the past 14 ka should reveal three recurring intervals of generally steeper inclination due to a dominant NGP longitudinal band in Europe. We find that the Fennoscandian PSV does indeed show these intervals of generally steeper inclination for the time periods expected, supporting the hypothesised periodic NGP variation, which may represent an inherent feature of the geodynamo.

1. Introduction

The study of natural remnant magnetisation (NRM) acquired by sediments, igneous rocks, and archaeological finds can be used to reconstruct geomagnetic field variations for the period predating the observed geomagnetic field record (e.g. older than 450 years). Regional reconstructions of directional geomagnetic field variations, or palaeomagnetic secular variation (PSV), are important for interdisciplinary uses, such as the construction of palaeomagnetic geochronologies for sediment cores (e.g. Saarinen, 1999; Kotilainen et al., 2000; Ojala and Tiljander, 2003; Barletta et al., 2010; Stanton et al., 2010; Lougheed et al., 2012). Specifically, by comparing reconstructed PSV in sediment cores to regional PSV master curves (e.g. Turner and Thompson, 1981; Snowball et al., 2007), the age of sediment deposition can be inferred. Palaeomagnetic dating methods are especially useful in deglacial environments, where

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^{14}C dating is made difficult by a lack of suitable organic material. PSV records included in the existing Fennostack (Snowball et al., 2007) PSV master curve for Fennoscandia are limited to the past 10 ka, due to the presence of the Fennoscandian ice sheet during earlier times. Extending the Fennoscandian PSV record further back in time requires selecting sites from suitable ice-free locations where NRM could feasibly have been recorded.

Reconstructions of PSV also serve to give valuable insight into the origin and behaviour of the geomagnetic field. For example, PSV data from strategic sites from different regions of the world are important as input for data-driven model reconstructions of global temporal variations in the Earth's magnetic field (e.g. Genevey et al., 2008; Valet et al., 2008; Nilsson et al., 2010; Korte et al., 2011). Recent analyses of results from data-driven global models have suggested the presence of millennial scale repetitive patterns in the geodynamo. Nilsson et al. (2011) noted an approximate cyclicity of approximately 1350 years in north geomagnetic pole (NGP) latitude for the Holocene, and a similar cyclicity was also noted by Korte et al. (2011) for the same period. Nilsson et al. (2011) also found two dominant modes of NGP longitude, shifting between longitudinal bands centred over North America and Europe. Based on different time series analyses of a global Holocene sedimentary database, Panovska et al. (2013) concluded that, although power is present at this period, it does not dominate the observed secular variation spectrum. The aforementioned studies all put high demands on the quality and/or quantity of input data and are therefore limited to the past 10 ka. In this study, we aim to construct a well-dated, regional PSV record for the Fennoscandian region that covers the deglacial period in the late Pleistocene and the early Holocene, i.e. the period 14–10 ka before 1950 AD (all subsequent ages in this study are reported relative to 1950 AD). An investigation of this earlier period will enable further examination of millennial scale patterns in the geodynamo, as well as providing researchers in the region with a PSV master curve for the deglacial period.

In this study, we examine a number of previously published late Pleistocene to early Holocene (14–10 ka) records in the wider Fennoscandia region, and also new PSV data from Baltic Sea long core sediment records. We evaluate the quality of PSV data from various locations, while also assessing geochronologies, updating them where necessary, using ongoing improvements in ^{14}C calibration and the latest understanding regarding the ages of pollen zones. By updating the geochronologies, we show that the PSV records from various sites are contemporaneous. We select data from the most suitable records and amalgamate them to create a composite deglacial PSV "master curve" for the region, which will provide a useful dating template for future researchers. We subsequently use this deglacial PSV master curve, along with existing Holocene data, to further test current hypotheses of temporal patterns in NGP latitude and longitude (Korte et al., 2011; Nilsson et al., 2011), with a specific focus on Fennoscandia.

2. Background

In Sweden and Finland, high-resolution PSV studies using continuous sediment records with good absolute geochronological control, including those with annually laminated (varved) lake sediments, have previously been carried out for the Holocene. Pioneering attempts by Ising (1943), Griffiths (1955) and Granar (1958) to measure annual variations in PSV based on varved clays were hindered by overly shallow inclinations, most likely due to sloping beds and current flows (reviewed by Griffiths et al., 1960). Successful studies were carried out by Mörner and Sylwan (1989) at the Swedish lake of Kassjön. Later, the lakes Alimmainen Savijärvi and Nautajärvi were studied in Finland (Ojala and Saarinen, 2002; Ojala and Tiljander, 2003), and the lakes Byestadsjön, Furskogstjärnet, Mötterudstjärnet, Sarsjön and Frängsjön were studied in Sweden (Snowball and Sandgren, 2002, 2004; Zillén, 2003). These studies were synthesised by Snowball et al. (2007), who stacked data from various sites to produce a Fennoscandian PSV master curve for the Holocene, known as Fennostack. More recent studies on suitable lakes in Sweden (Kälksjön) and Finland (Lehmilampi and Kortejärvi) have provided even higher resolution Holocene PSV reconstructions at individual locations (Haltia-Hovi et al., 2010; Stanton et al., 2010; Haltia-Hovi et al., 2011).

All of the Fennoscandian PSV sites described in the previous paragraph are limited to the past 10 ka, due to the presence of the Scandinavian ice sheet. Most of the sites associated with the Fennostack master curve were covered by ice sheets until after the end of the Younger Dryas 11.6 ka ago (Fig. 1), preventing continuous deposition of sediments. After the retreat of the ice sheets, the delayed response of post-glacial isostatic rebound means that some lakes in low-lying coastal areas only became isolated from the Baltic Sea significantly after deglaciation (Eronen et al., 2001). Researchers interested in continuously varved lake sediment sequences have thus had to turn to lakes that are further inland, which were covered by ice until after the Younger Dryas. Such lakes can also problematic: The record at Byestadsjön (Fig. 1), despite its apparently suitable location, does not extend further back than approximately 10 cal ka BP, below which sandy silt, unsuitable for PSV reconstructions, occurs, due to the lake's proximity to the front of the glacier (i.e. glacio-proximal) and being in an area dominated by dead ice. These glacio-proximal sites can also be affected by inclination shallowing due to the aforementioned sloping beds, as well as gravitational effects that cause magnetic anisotropy and clay compaction (Griffiths et al., 1960; Borradaile and Almqvist, 2008), while (post-) depositional disturbances in glacio-proximal varves can lead to increased scatter in both inclination and declination data, as noted in Fennoscandia by Bakhmutov et al. (2006). Bakhmutov et al. (2009) also found that glacio-distal varves yielded better PSV data. Baltic Sea sediments have also been used for PSV reconstructions, but continuous long-term reconstructions are limited by the authigenic formation of greigite (Fe_3S_4) in sediment during the Ancylus Lake freshwater phase of the Baltic Sea (approx. 11–8 ka ago). The greigite acquires a post-depositional chemical remanent magnetisation (CRM) and can make sediments unsuitable for PSV analysis (Sohlenius, 1996; Snowball, 1997; Lougheed et al., 2012; Reinholdsson et al., 2013). However, sediments both younger and older than the Ancylus Lake phase have been found to yield robust PSV data, whereby a characteristic remanent magnetisation (ChRM) could be identified (Kotilainen et al., 2000; Lougheed et al., 2012).

In this study, we present a number of candidate sites from existing data, where robust and well-dated PSV data for the 14–10 ka period are present, from strategic locations whereby the NRM preservation difficulties detailed in the previous paragraphs are minimised and/or not present.

3. Field and laboratory work

As well as presenting candidate sites based on existing data, we also present a candidate site based on new PSV data retrieved from the Baltic Ice Lake sections of a long core sediment core from the Baltic Sea. The Baltic Ice Lake was the glacio-proximal ice dammed lake phase of the Baltic Sea, which terminated at 11.7 cal ka BP (Björck, 1995; Saarnisto and Saarinen, 2001). To evaluate the Baltic Sea as a deglacial archive for PSV, core MSM16/1-040-05 (henceforth 040-05) was retrieved from the Bornholm Basin of the Baltic Sea (55°22.18′N, 15°27.29′E) from a water depth of 93.6 m (see Fig. 1), on board R/V *Maria S. Merian* during August 2010. The